

A clean signal for a top-like isosinglet fermion at the Large hadron Collider

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Abstract

We predict a clean signal at the Large Hadron Collider ($\sqrt{s}=14\text{TeV}$) for a scenario where there is a top-like, charge $+\frac{2}{3}$ vectorlike isosinglet fermion. Such a quark, via mixing with the standard model top, can undergo decays via both flavour-changing Z-boson coupling and flavour-changing Yukawa interactions. We concentrate on the latter channel, and study the situation where, following its pair-production, the heavy quark pair gives rise to two tops and two Higgs boson. We show that the case where each Higgs decays in the $b\bar{b}$ channel, there can be a rather distinct and background-free signal that can unveil the existence of the vectorlike isosinglet quark of this kind.

1 Introduction

Our present knowledge about elementary particles and their interactions upto the energy scale of several hundred GeV's is encapsulated in the theory called the Standard Model(SM). The SM, a renormalizable gauge theory of strong and electroweak interactions based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$, gives a successful explanation for most of the phenomena governing fundamental processes, and is in excellent agreement with the experimental data to date. However, there are a number of unanswered questions which motivates us to think beyond the SM. These include, just to name a few, the flavour and naturalness problems, the absence of a cold dark matter candidate in the spectrum, and the origin of neutrino masses and mixing[1]. They have led to a plethora of conjectures extending the SM.

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On the experimental side, a golden opportunity to test many of these conjectures has come through the Large Hadron Collider(LHC), which aims at not only discovering the only missing piece of the SM, namely the Higgs boson, but also looking for new physics beyond it.

One of the various ideas beyond the SM is to extend the fermionic sector of the SM by postulating existence of either a sequential fourth generation[2] or vector-like fermions. The electroweak precision data strongly constrains the existence of extra chiral fermions. On the other hand, vector-like fermions, have left-and right-handed components with the same transformation property under $SU(2)$, and are considerably free from the aforementioned constraints. They can have gauge invariant mass terms of the form $\bar{\psi}_L \psi_R$, which do not arise from the electroweak symmetry breaking mechanism, and should be traced to some new physics scale. Thus their signature is of immediate interest if that scale is accessible to the LHC, with the fond hope that they might contain some clue to the flavour problem.

Vectorlike fermions appear as singlets, doublets or triplets under $SU(2)$, in many options beyond the Standard Model(BSM) like Little Higgs Model[3], composite Higgs model[4]and extra dimensional models[5]. They also appear in some grand unified theories like E_6 [6], which once got impetus from considerations underlying superstring theories. In particular, vectorlike isosinglets also play a role in the $\Delta F = 2$ effective Lagrangian analysis studies[7]. Also, it has been pointed out that models with such an extended quark sector can give rise to quark electric dipole moment at the two-loop level due to the lack of Glashow-Illiopoulos-Maiani(GIM) suppression, thereby implying constraints on the model parameter space(s)[8]. The collider phenomenology of such an isosinglet vector fermion has been studied from various angles [9]-[32].

Here we focus on an $SU(2)$ singlet, charge $\frac{2}{3}$ vectorlike quark. It should be noted that down-type vectorlike isosinglets, too, have been considered extensively in the literature[8],[29]-[32]. The vectorlike quark is pair-produced at the LHC in the same way as the top quark, subject, of course, to the inevitable kinematical suppression if its mass is higher. Such a quark, however, has additional decay channels, which can make it distinct. The main features responsible for such distinction are its isosinglet character, and its capacity to mix with the top, once $SU(2) \times U(1)$ is broken. As a result of doublet-singlet mixing in the left chiral sector, such a quark, named t' here, has flavor changing interactions both with the higgs boson(H) and the Z boson. We propose to utilise the resulting decay channels, namely $t' \rightarrow tH$ and $t' \rightarrow tZ$. In particular, we find that the former channel leads to a rather

unique and background free signature arising from a $t\bar{t}HH$ state.

On account of mixing between the SM fermions and their SU(2) singlet counterparts, many observables are expected to be different from the Standard Model predictions, specially in the sector involving third family. We assume a situation where Higgs is discovered already and its mass is approximately known. We use such a Higgs as an instrument to investigate the production and decay of exotic top-like quark into channels which hardly have Standard Model backgrounds. We consider two Higgs masses, namely $m_H = 120$ GeV and $m_H = 130$ GeV. In order to maximize our signal rates, we let the Higgs decay in each case into the final state with maximum branching ratio, namely $H \rightarrow b\bar{b}$. We show that, using the consequent 6b final states (including decays of the top quarks as well), one can construct signals with very little SM backgrounds. Tagging five b's out of six in each case, with appropriate event selection criteria, proves to be sufficient for this purpose. We demonstrate that such a signal can allow us to probe in a discriminating fashion a large part of the parameter space consisting of the t' mass and its mixing with the t . The rest of the paper is organised as follows. Section 2 contains an outline of the scenario, statements on the signal looked for, a reminder of the constraints on various parameters, and a resume of the methodology adopted. The results are presented in Section. 3. We summarise and conclude in Section 4.

2 The scenario, the signal and the methodology

2.1 The scenario and its signals

As has been said already, we consider a minimal extension of the SM with the inclusion of a top-like vector isosinglet, t'_L ($3, 1, +\frac{4}{3}$), t'_R ($3, 1, +\frac{4}{3}$) to the matter content of the SM. The gauge boson and the Higgs sector remains unchanged.

t' can be produced in pair via the strong interactions or singly via electroweak processes. We concentrate here on the former channel, which at the parton level corresponds to $gg \rightarrow t'\bar{t}'$ and $q\bar{q} \rightarrow t'\bar{t}'$ essentially arising from the gluon coupling of the heavy quark:

$$L_{QCD} = -\iota g_s \bar{t}' \gamma_\mu t' G_\mu \quad (1)$$

Neglecting the small contribution from electroweak diagrams, the pair production cross section for an isosinglet fermion and a chiral fourth generation

fermion is the same[33],[34].The production cross section depends only upon the mass of t' and goes down with increase in the mass.

Once the $SU(2) \times U(1)$ symmetry is broken, the most substantial mixing of t' can take place with the top, as there are rather stringent bounds on mixing with the first two generations[14]. It must be remarked that there have been studies which considered the mixing with the lighter generations, which can affect, for example, the single production of vector like quarks through the electroweak channels[35]. As a result of such mixing, the four charge $\frac{2}{3}$ quarks in the weak basis are related to the corresponding mass eigenstates by

$$\begin{bmatrix} u_0 \\ c_0 \\ t_0 \\ t'_0 \end{bmatrix} = U \begin{bmatrix} u \\ c \\ t \\ t' \end{bmatrix}, \quad U = \begin{bmatrix} V_{3 \times 3}^\dagger & W_{3 \times 1} \\ X_{1 \times 3} & v_{1 \times 1} \end{bmatrix} = \begin{bmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* & W_{dt'} \\ V_{us}^* & V_{cs}^* & V_{ts}^* & W_{st'} \\ V_{ub}^* & V_{cb}^* & V_{tb}^* & W_{bt'} \\ X_{u4} & X_{c4} & X_{t4} & v_{4t'} \end{bmatrix} \quad (2)$$

V is the Standard Model CKM matrix. In such a basis the mass matrix for the down type quarks is diagonal. The mass matrix(M^u) for the up type quarks is

$$M^u = \begin{bmatrix} M_{\bar{q}_L q_R} & M_{\bar{q}_L t'_R} \\ M_{\bar{t}'_L q_R} & M_{\bar{t}'_L t'_R} \end{bmatrix} \quad (3)$$

where $q_{L,R} = (u, c, t)_{L,R}$, $M_{\bar{q}_L q_R}$ is 3×3 mass matrix of the SM particles, $M_{\bar{q}_L t'_R}$ is 3×1 , $M_{\bar{t}'_L q_R}$ is 1×3 and $M_{\bar{t}'_L t'_R}$ is the mass term for t' . $M_{\bar{t}'_L q_R}$ and $M_{\bar{t}'_L t'_R}$ do not arise from the Yukawa couplings. M^u is diagonalized by the bi-unitary transformation : $U^\dagger M^u U' = M_{diag}^u$, where U' is parametrized analogously to U but in spite of right handed fermions being there in the Yukawa couplings, the elements of U' do not appear as such.

With the structure of the mixing matrix being what is shown in equation(2), the Standard Model CKM matrix is no longer unitary, and instead forms a block in the unitary 4×4 mixing matrix U . The V and W together form the 4×3 charged current mixing matrix. The violation of CKM unitarity leads to a breakdown of the Glashow-Iliopolous-Miami(GIM) mechanism, and leads to the flavor changing neutral current (FCNC) processes ($t \rightarrow cZ$) and ($t \rightarrow cH$) in the top sector [10, 11]. As mentioned above, t' decays to the SM fermions along with either the electroweak gauge bosons (W^\pm, Z) or Higgs boson(H) at the tree level. The charged current interaction ($t' \rightarrow bW^+$) is given by

$$L_{cc} = \frac{g W_{bt'}}{\sqrt{2}} \bar{t}'_L \gamma_\mu b_L W_\mu^+ \quad (4)$$

On account of mixing with the top quark we have Flavor changing neutral

current interactions with Z boson given by

$$L_{neutral} = \frac{gV_{tb}^*W_{bt'}}{2Cos_W} \bar{t}_L' \gamma_\mu t_L Z_\mu \quad (5)$$

And the interaction of t' with Higgs boson and the Flavor changing Yukawa coupling is

$$L_{yukawa} = -y_{t'} \bar{q}_{Li} H^c t_R' + h.c \quad (6)$$

where $y_{t'}$ in this comes to be $\frac{g}{2M_W} V_{tb}^* W_{bt'} M_{t'}$. In addition to the above yukawa coupling there are terms proportional to $\bar{t}_L' q_R$ and $\bar{t}_L' t_R'$ which arise on account of the fact that it is not possible to diagonalize the mass and Yukawa matrices simultaneously.

Following the simplified version of the mixing matrix used in [11], we describe all the interactions of t' by the following mixing matrix

$$U = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & Cos\theta & Sin\theta \\ 0 & 0 & -Sin\theta & Cos\theta \end{bmatrix} \quad (7)$$

Where its interactions with all quarks of the first two generations are neglected. We also neglect the interactions of the SM quarks across the generations. The elements of the mixing matrix are chosen with the motivation to have considerable flavor changing decay modes in addition to the charge changing decay modes.

We concentrate on one of the decay process of t' , namely, ($t' \rightarrow tH$). For the sake of our current work we assume that the Higgs boson has already been discovered with approximately known mass. This particular decay channel has already been used as a tool to study the discovery potential of Higgs[13, 26, 27] but with a different final state. In [28] though the final decay of h considered is also to $b\bar{b}$ but it is in context of “Little Higgs model” where there are extra gauge and Higgs bosons along with t' . The further decay chain we consider is where both the tops decay to bW and both the Higgs to $b\bar{b}$. i.e

$$pp \rightarrow t'\bar{t}' \rightarrow hth\bar{t} \rightarrow b\bar{b}bW^+b\bar{b}bW^- \quad (8)$$

The final state consists of 6b's and 2 W's, out of which we attempt to identify 5b's and predict the signal for 5b+X final state. As we show in this work, this turns out to be a rather clean signal with very low SM background.

Direct and indirect searches for the vector fermions put constraints on the mass and couplings of t' and the mixing angle θ , between t and t' . Among them, direct searches imply the following bounds:

- Considering $t' \rightarrow W^+ q$ as the only possible decay chain, the lower limit on the mass of t' is 358 GeV at 95% C.L. by the CDF collaboration[33] at center of mass energy, $\sqrt{s}=1.96$ TeV
- The DO collaboration puts the lower limit in the channel of W+jets decay, at the 95% CL to be 258 GeV[34] at $\sqrt{s}=1.96$ TeV.
- The latest study by ATLAS set the lower limit on the mass of t' at $m_{t'} < 404$ GeV at the 95% C.L. assuming 100% decay through bW^+ mode[36] at the center of mass energy, $\sqrt{s}=7$ TeV.
- Assuming 100 % branching fraction for the decay $t' \rightarrow tZ$, t' with any mass less than 475 GeV is excluded at 95 % confidence level by CMS detector at the LHC[37] at $\sqrt{s}=7$ TeV.
- The R_b ratio given by, $R_B = \frac{\Gamma(Z \rightarrow b\bar{b})}{\Gamma(Z \rightarrow \text{hadrons})}$, gives a strong constraint on the t - t' mixing angle, θ to be $\theta \leq 25^\circ$ [18].

For the purpose of our current work, we consider the lowest mass to be 350 GeV, and make no specific assumption about branching ratios in the three decay channels.

2.2 Methodology

For numerical calculations, we have used CalcHEP v2.5.6[38] and a CalcHEP-PYTHIA interface program[39] along with PYTHIA-6.4.24[40]. The production cross-section of the isosinglet quark pair and the decay of t' , \bar{t}' is calculated using CalcHEP. In order to do so, a new model with the new interactions based on the mixing matrix considered, was added to the existing list of CalcHEP models. We have taken $m_t=172$ GeV, and used CTEQ6L parton distribution functions (PDF), for the center-of-mass energy $\sqrt{s}=14$ TeV. We chose the following benchmark points for our calculation: After

Parameter	Value
$M_{t'}$ [Gev]	350,400,500
mixing angle $t - t'$, θ	5,10,15
M_h [GeV]	120,130

Table 1: Benchmark Points

calculating the production cross section and branching fractions for all the

benchmark points by CalcHEP, the output is transferred to the CalcHEP-PYTHIA interface program[39]. The interface program is provided with the appropriate selection cuts. Subsequently, PYTHIA is used for obtaining rates in the desired final state of $5b+X$.

The SM background in this case is calculated at the parton level for the signal $pp \rightarrow hht\bar{t}$ using CalcHEP v2.5.6[38]. The only on shell process which gives rise to this signal in the SM is $pp \rightarrow t\bar{t} \rightarrow hht\bar{t}$, as a result the background is very small. b-identification efficiency has been taken to be 50%. We have not taken into account the effect of, for example, charm-induced jets faking b's. We reconstruct the invariant mass of all the bb pairs which survive the first three of the selection cuts listed below, and follow the criteria explained there, the background for the signal $5b+X$ is very low in comparison to the signal.

We have used the following selection criteria on the minimum of five b's required in our stipulated final state:

- Each of the identified b's should have $E^T > 40.0$ GeV.
- Each b jet should be central, with pseudorapidity, $|\eta| < 2.5$.
- We implement b-tagging efficiency of 50% i.e $\epsilon_b \sim 0.5$.
- As a final step we calculate the invariant mass for all the possible combinations of b pairs. We impose the following restriction on the calculated invariant mass(m_{bb}) i.e $m_{bb} = (M_h \pm 15)\text{GeV}$.
We get our final numbers by counting all the events(NH) which have at least two such b pairs with their calculated invariant mass falling in the above limit. We predict our signal using this number.

3 Results

We are presenting the results at the leading order(LO), and thus our estimate can be called conservative. Our final state consists of six b's and two W's. A similar use of the final state comprising six b's has been considered in [20]. However, the suggested signal, clean as it is, has suppressed rates due to the requirement of i)identification of all the six b's and ii) the simultaneous tagging of an isolated lepton. We, in contrast, give up the lepton tagging requirement. Moreover, we suggest identifying only five out of six b's, with the proviso that four out of them display two individual peaks, each at the mass of the Higgs boson which is presumably detected before our analysis takes place. We succeed in considerably enhancing the event rates

in this manner, while at the same time having negligible backgrounds, with our chosen acceptance criteria. As is clear from the plot, figure 1, the pair production cross section of $t'\bar{t}'$ decreases with $M_{t'}$ since it depends only on the mass. We find that the production of signal at the parton level, $hht\bar{t}$ in the

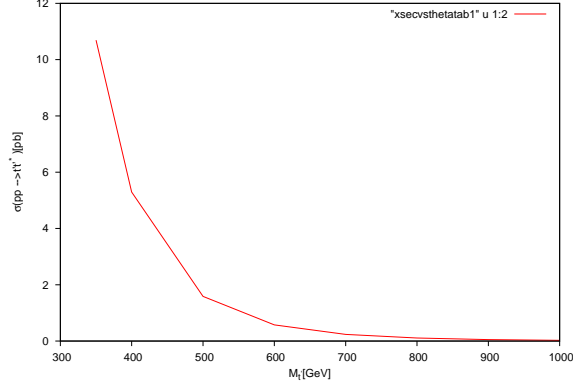


Figure 1: Production Cross section of $t'\bar{t}'$ with the mass of t' at $\sqrt{s}=14$ TeV

SM, is weaker by atleast 10^2 order of magnitude in comparison to the lowest signal(for $M_{t'}=500$ GeV, $M_h=130$ GeV and $\theta = 15$) in our model as can be seen in the table (2) and (3). We present our results as the cut-flow chart

M_h (GeV)	Xsection[pb]
120	0.00060
130	0.00044

Table 2: Production Cross section in the Standard Model for the signal $pp \rightarrow hht\bar{t}$ at $\sqrt{s}=14$ TeV

$M_{t'}$	M_h [GeV]	Cross-section[pb]		
		$\theta = 5$	$\theta = 10$	$\theta = 15$
350	120	0.4272	0.4105	0.3826
	130	0.3590	0.3583	0.3355
400	120	0.2430	0.2365	0.2232
	130	0.2308	0.2236	0.2101
500	120	0.07089	0.06931	0.06520
	130	0.06949	0.06761	0.06324

Table 3: Production cross section of $pp \rightarrow t\bar{t}hh$ in our model at $\sqrt{s}=14$ TeV

for all the considered benchmark points and the invariant mass distributions

$M_{t'}$ [GeV]	Cut	Cross-section[pb]					
		$M_h=120 \text{ GeV}$			$M_h=130 \text{ GeV}$		
		$\theta = 5$	$\theta = 10$	$\theta = 15$	$\theta = 5$	$\theta = 10$	$\theta = 15$
350	$E_T^b > 40.0 \text{ GeV}$	0.1993	0.1907	0.1809	0.1730	0.1664	0.1575
	$|\eta_b| < 2.5$	0.1735	0.1660	0.1574	0.1519	0.1462	0.1378
	$NH \geq 2$	.01061	.01046	.0098	.0099	.0094	.0089
400	$E_T^b > 40.0 \text{ GeV}$	0.1155	0.1120	0.1061	0.1072	0.1038	.0973
	$|\eta_b| < 2.5$	0.1023	.0951	.0939	.0954	.0925	.0868
	$NH \geq 2$	.00606	.00593	.00557	.0060	.0060	.0054
500	$E_T^b > 40.0 \text{ GeV}$	.0338	.0323	.0304	.0321	.0311	.0292
	$|\eta_b| < 2.5$	.0307	.0293	.0275	.0293	.0283	.0267
	$NH \geq 2$	.00175	.00165	.00155	.0017	.0016	.0016

Table 4: Cutflow table for various benchmark points for $M_h=120 \text{ GeV}$ and $M_h=130 \text{ GeV}$ at $\sqrt{s}=14 \text{ TeV}$

of $b\bar{b}$ pairs. We compute our results for different values of $m_{t'}$ and M_h and mixing angle θ . In spite of a substantial reduction of the signal due to tagging efficiency of 50% per b , our predicted signal is still good enough to be observed at the LHC at the integrated luminosity of 30 fb^{-1} . We find the following trends in our results as can be seen from the table 4.

- For a given value of $M_{t'}$ and M_h change in θ does not make much of a difference(.2fb-.6fb)[figure 2, 3].
- For a given value of M_h and θ dependence on the $M_{t'}$ is the strongest. It changes the cross section for the signal by 8fb-10fb.
- For a given $M_{t'}$ and θ the change in Higgs mass does not really make a difference.
- Also as the $M_{t'}$ goes from 350 GeV to 500 GeV, the change in M_h and θ hardly makes any difference on the signal cross-section.

We plot the invariant mass distribution of all the combinations of b pairs for the events which survive the first three selection criteria. We find that this distribution has two peaks corresponding to the reconstructed Higgs mass with in the required mass range ($m_{b\bar{b}} = (M_h \pm 15)\text{GeV}$), as in figure 4,5, satisfying our fourth selection criterion, for all our benchmark points. We present here the distribution for two points only i.e. fig.4, 5).

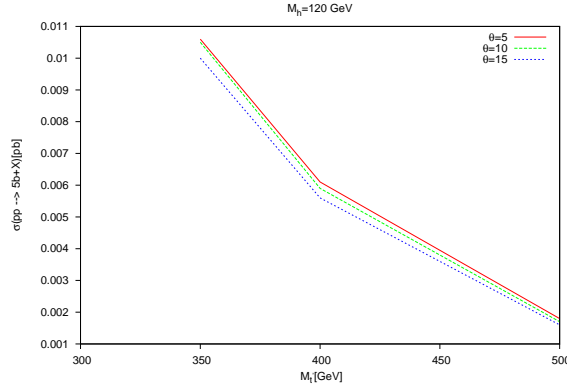


Figure 2: Cross section for the final state (5b+X) with the mass of t' for various values of mixing angle θ and $M_h=120$ GeV at $\sqrt{s}=14$ TeV

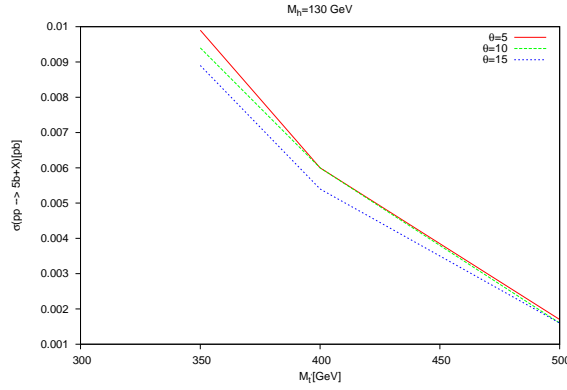


Figure 3: Cross section for the final state (5b+X) with the mass of t' for various values of mixing angle θ and $M_h=130$ GeV at $\sqrt{s}=14$ TeV

4 Summary and Conclusions

We have calculated the particular signal (5b+X), in the framework of a model with a top like($+\frac{2}{3}$) vector fermion, (t'), in addition to the SM particles. We assume that it mixes only with the top quark. We ignore not only the interactions of t' with first two generations but also the interactions of the SM quarks across the generations in the mixing matrix, U in equ.7. As a result of the mixing with the top, t' has Flavor Changing Neutral interactions with Z and H bosons. We make use the interaction with Higgs boson and follow a particular decay mode ($t' \rightarrow ht$) of t' and further consider the decay of higgs to $b\bar{b}$. Using CalcHEP, PYTHIA and CalcHEP-PYTHIA interface programs, we predict an observable signal of 5b+X from a final state signal of 6b's and 2W's, at the LHC at the center of mass energy, $\sqrt{s}=14$ TeV. We

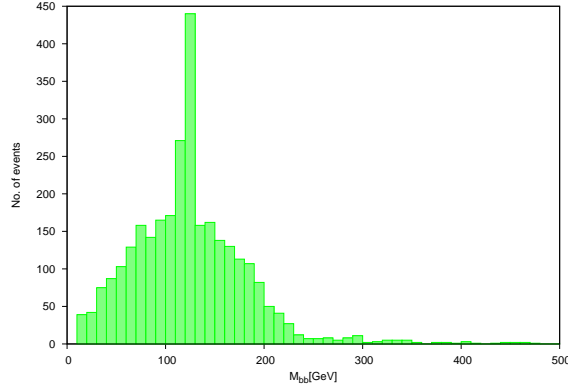


Figure 4: Invariant mass distribution of $b\bar{b}$ for $m_{t'}=350$ GeV, mixing angle $\theta = 15$ and $M_h=120$ GeV for $\sqrt{s}=14$ TeV

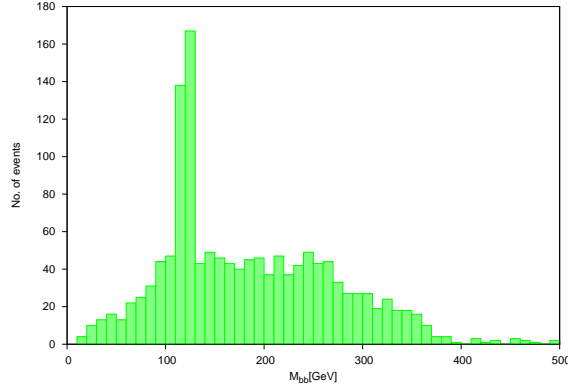


Figure 5: Invariant mass distribution of $b\bar{b}$ for $m_{t'}=500$ GeV, mixing angle $\theta = 15$ and $M_h=120$ GeV for $\sqrt{s}=14$ TeV

consider the situation when the Higgs boson is already discovered, so that its mass is a known quantity, and can be used to identify two b-pairs with invariant mass around the mass of the Higgs, taken here to be in the region 120 GeV-130 GeV. We find that in spite of the rather ambitious proposal of tagging five b's, we get, after all cuts, a signal of the order of few fb which is stronger by at least 10^2 in comparison with the SM background. Since all our results are at the leading order so the predictions we make about the signal are rather conservative. We conclude that an integrated luminosity of 30 fb^{-1} should be sufficient to either find out or rule out the existence of t' in the mass range 350 GeV-500 GeV.

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Note: As we were in the process of submission, a similar work(arxiv:1204.2317) appeared which considers the same decay channel of t' and the subsequent h decay as we do but the analysis done is for different final states.

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